Effects of Annealing Process on the Formability of Friction Stir Welded Al-Li alloy 2195 Plates

Po-Shou Chen, Carolyn Russell

Abstract

Large rocket cryogenic tank domes have typically been fabricated using Al-Cu based alloys like Al-Cu alloy 2219. The use of aluminum-lithium based alloys for rocket fuel tank domes can reduce weight because aluminum-lithium alloys have lower density and higher strength than Al-Cu alloy 2219. However, Al-Li alloys have rarely been used to fabricate rocket fuel tank domes because of the inherent low formability characteristic that make them susceptible to cracking during the forming operations.

The ability to form metal by stretch forming or spin forming without excessive thinning or necking depends on the strain hardening exponent “n”. The stain hardening exponent is a measure of how rapidly a metal becomes stronger and harder. A high strain hardening exponent is beneficial to a material’s ability to uniformly distribute the imposed strain.

Marshall Space Flight Center has developed a novel annealing process that can achieve a work hardening exponent on the order of 0.27 to 0.29, which is approximately 50% higher than what is typically obtained for Al-Li alloys using the conventional method. The strain hardening exponent of the Al-Li alloy plates or blanks heat treated using the conventional method is typically on the order of 0.17 to 0.19.

The effects of this novel annealing process on the formability of friction stir welded Al-Li alloy blanks are being studied at Marshall Space Flight Center. The formability ratings will be generated using the strain hardening exponent, strain rate sensitivity and forming range. The effects of forming temperature on the formability will also be studied. The objective of this work is to study the deformation behavior of the friction stir welded Al-Li alloy 2195 blank and determine the formability enhancement by the new annealing process.

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EM30 & EM10/NASA-Marshall Space Flight Center

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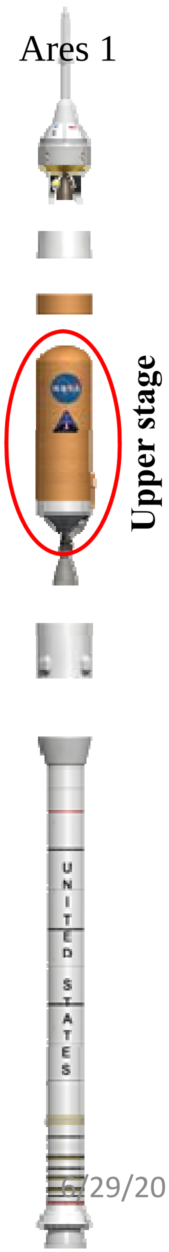
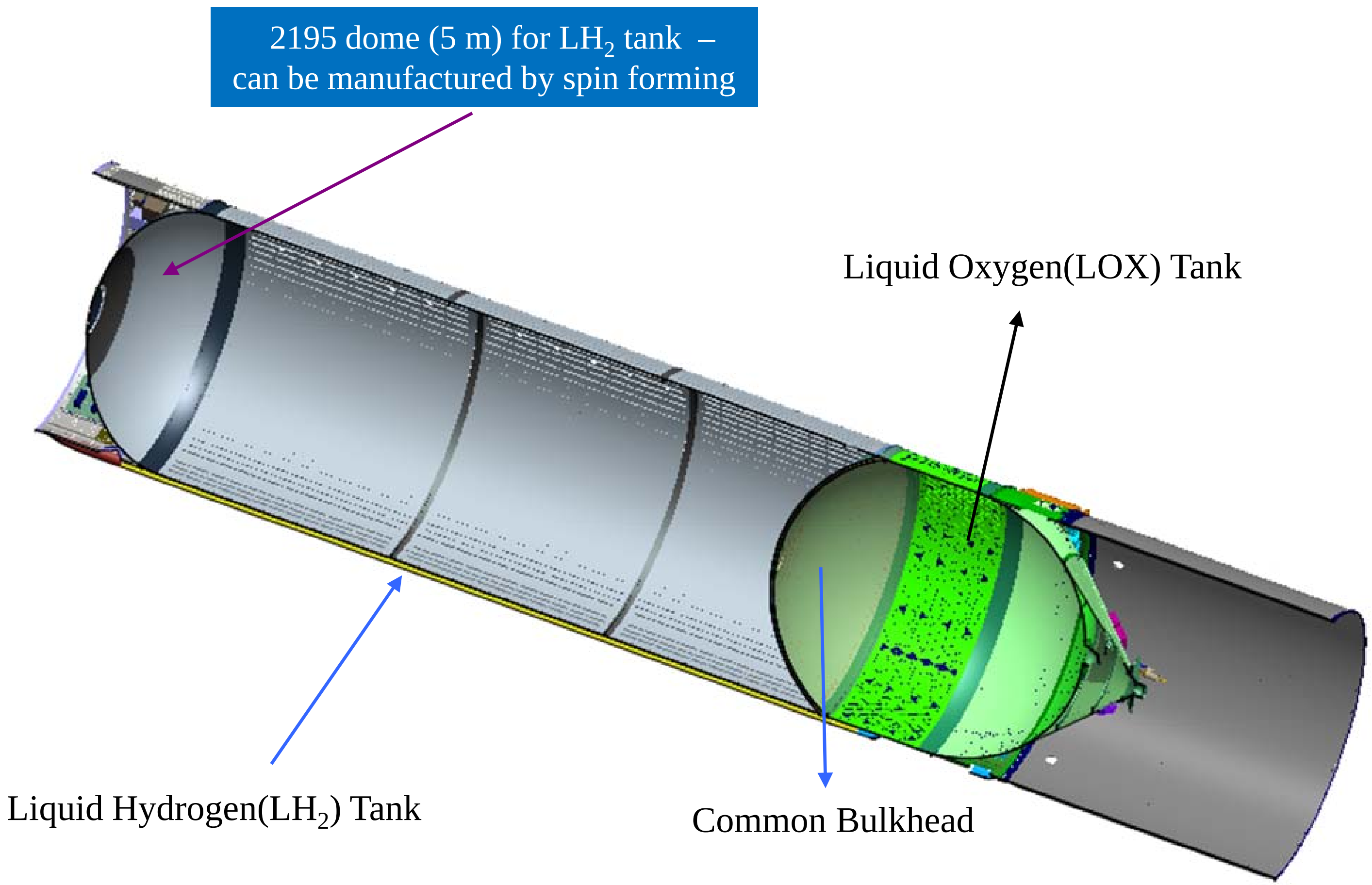
Spun-Formed Dome Development for Ares 1 Upper Stage LH_2 Tank



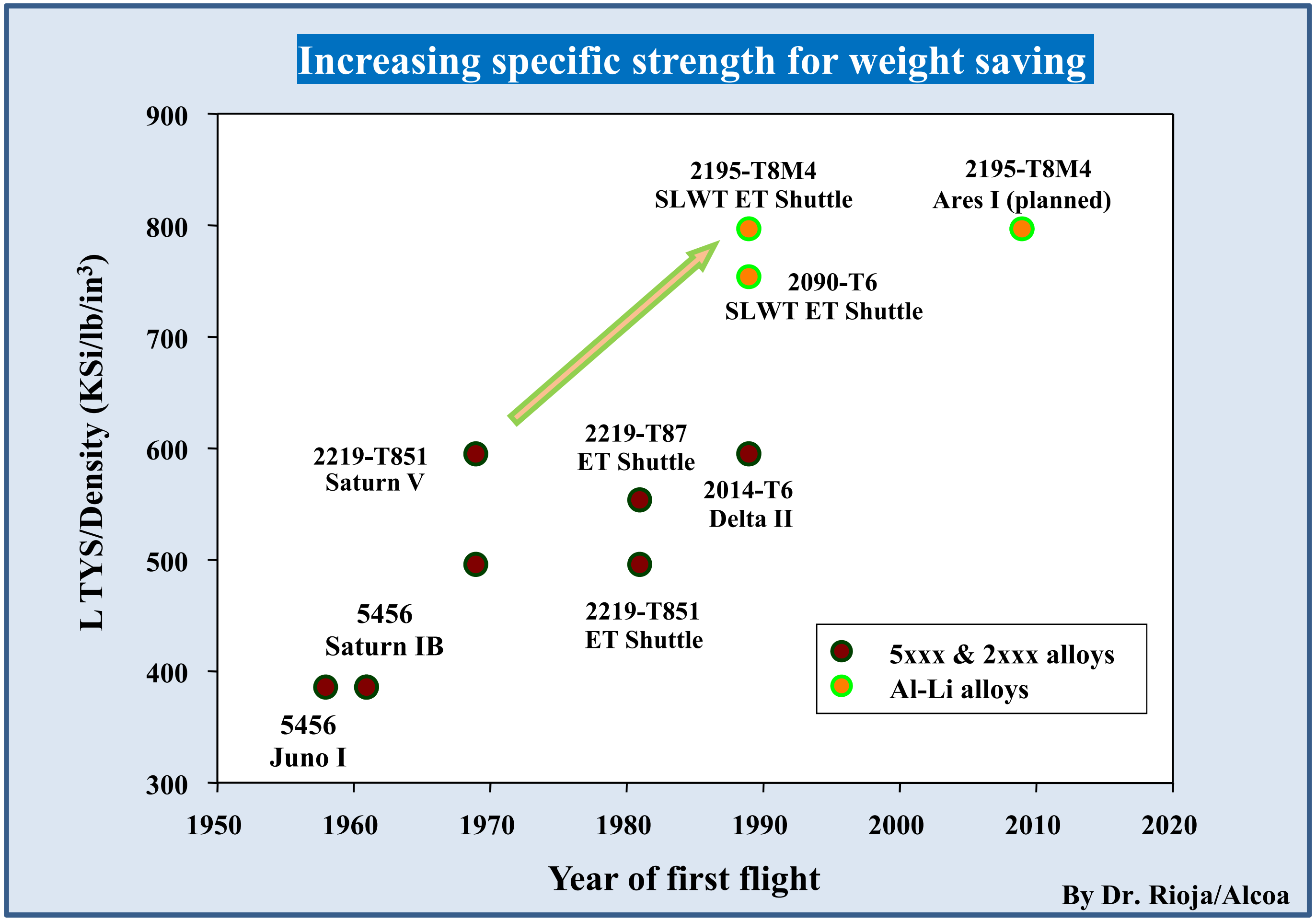


- 2195 dome is currently manufactured by gore construction, tedious & complex process
  - Spun formed 2195 dome can save weight & costs; being developed by NASA

Rocket Weight Saving Design Evolution for Al-Products

2195 nominal composition: **Al-4%Cu-1.0%Li-0.3%Ag-0.3%Mg-0.1%Zr**

- The Al alloy with the highest specific strength – most weight saving potential

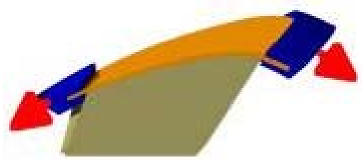


Spin Forming being Developed to Replace Current Gore Construction

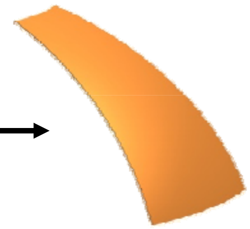
Traditional Approach – Gore Construction

Plate

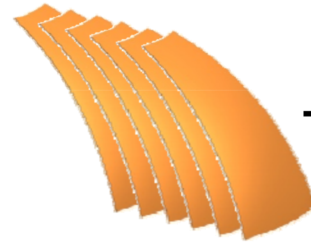
Stretch forming



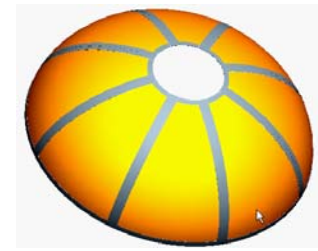
Mandrel



Dome Gore Panel

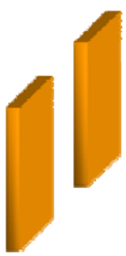


Dome Gores

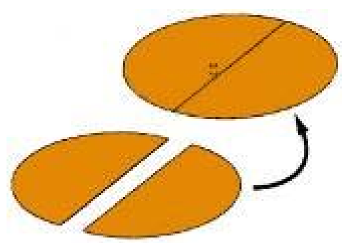


Welded Gore Assy. Dome

Developmental Spin forming Approach



Plate



FSW dome blank

Spin forming process

Spun Formed Dome

Benefits:

- Improved safety and mission success
- Reduced part count
- Reduced weld count

Mass Savings:

- Elimination of weld lands
- Higher strength material

Cost Savings:

- Reduced material quantity
- Reduced production labor

Status:

– Production application
  - Any Aluminum alloy domes
  - Up to 5.5 meter diameter

Development of 5 m Diameter Spun-formed Dome

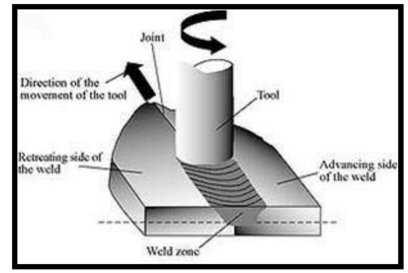
Aluminum-Lithium Alloys

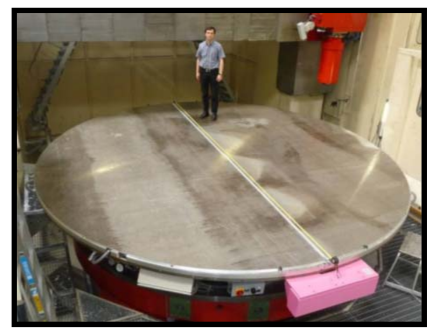
- High strength / weight ratio
- Good SCC resistance

Friction Stir Welding

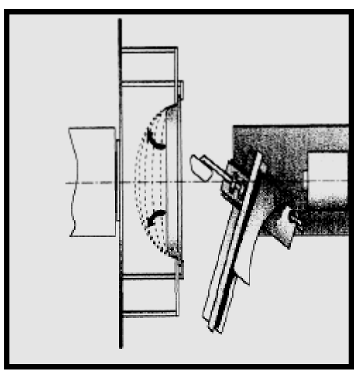
- Greater strength & ductility than
- fusion welding
- Low defect occurrence

FSW Spun Formed Dome
5 m dia. Al-Li 2195





Join 2 plates into a big blank



Spin Forming

- Single piece near net shape manufacturing
- Lower manufacturing costs
- Improved mass fraction
- Improved system reliability

Challenges for Spin Forming Technology Development

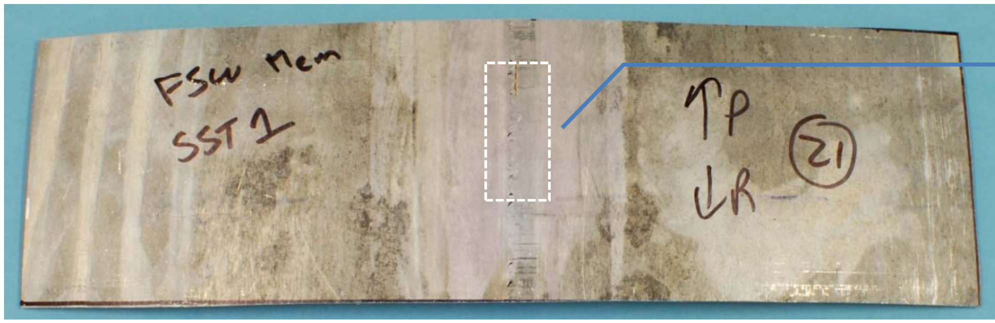
1. **Abnormal grain growth (AGG) in the FSW**
    - Grain size increase from 10 µm to more than 1 mm (more than 100 x increase)
    - AGG reduces the ductility/toughness to very low level
    - Working to optimize FSW, spin forming, and thermo-mechanical processing parameters for AGG mitigation

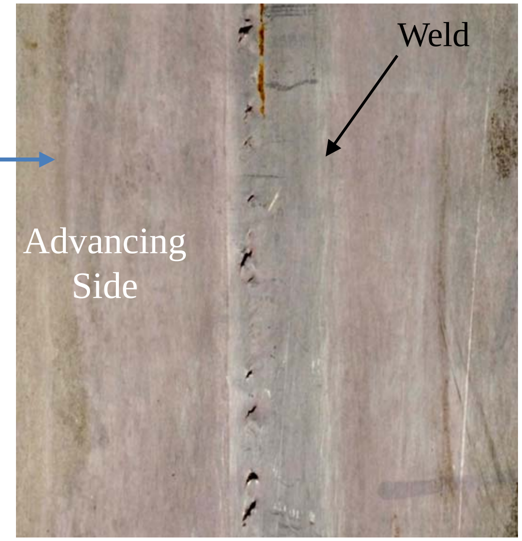
AGG in 2195 FSW

2. **Micro-cracking in the FSW**
    - Microcracks are located in the FSW
    - Microcracks are stress risers and make the dome susceptible to catastrophic failure
    - Developing a favorable post-weld anneal to prevent microcracking in FSW

Microcracks in 2195 FSW

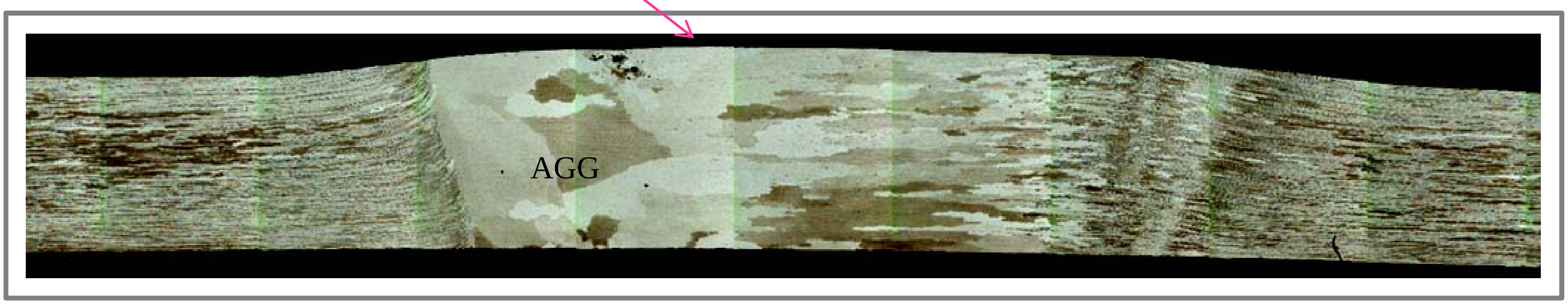
Micro-Cracking in the Dome FSW





Many cracks on the weld

Thickened weld after spin forming – a sign of inadequate formability



- Weld is thickened, indicative of weld being harder than the parent metal
- Poor formability led to extensive cracking on the weld
- AGG is present in the weld after T8 heat treatment

Formability Enhancement for Spun-Formed Dome

Formability Enhancement is a key to Spun-Formed Dome Development

- Formability is the ability of a sheet metal to maintain its structural integrity while being plastically deformed into a shape

Improvement in Formability Can be Made by Increasing Strain Hardening Exponent ("n") and strain rate sensitivity ("m")

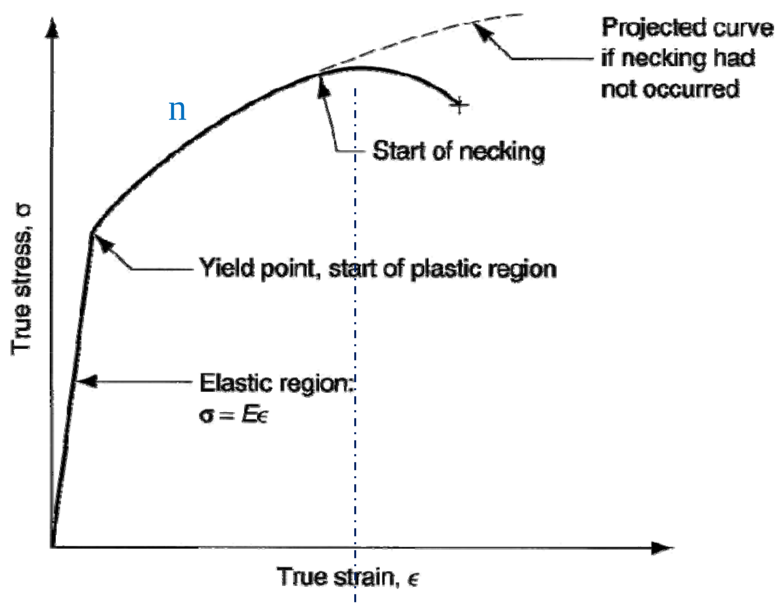
- High strain hardening coefficient can help strain distribution and delay necking
- High strain rate sensitivity can strengthen the necking zone and promote diffuse necking
- These parameters are microstructure dependent

A Formability Enhancing Novel Heat Treatment has been Developed at MSFC

- Show promise in enhancing formability by increasing the strain hardening exponent & strain rate sensitivity
  - ✓ The novel heat treatment can equalize the weld/parent metal hardness
  - ✓ And homogenous strain distribution without strain localization in the weld

Determine the Strain Hardening Exponent "n" by Tensile Testing

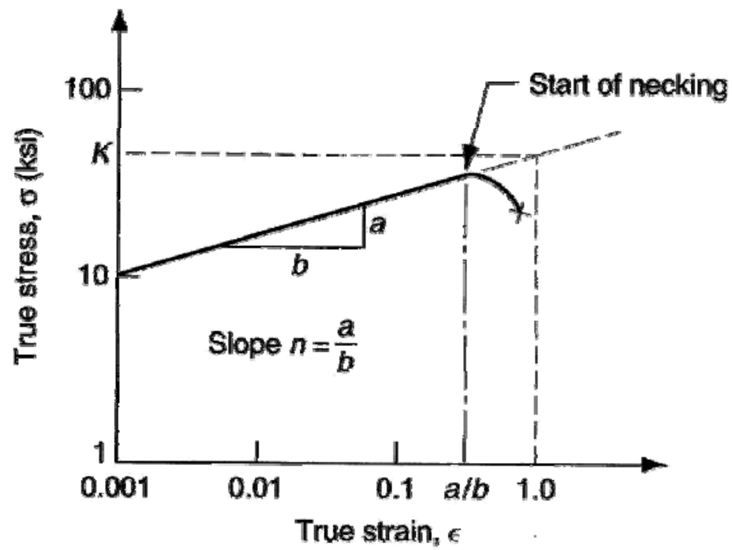
True stress-strain curve



True strain: $\boxed{\varepsilon = \ln(1+e)}$

True stress : $\boxed{\sigma_t = \sigma_e(1+e)}$

"n" determination



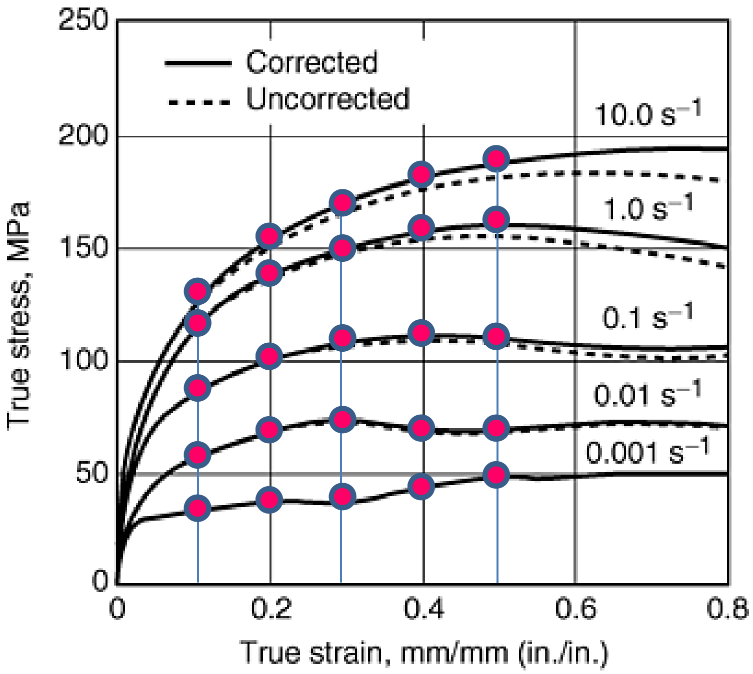
Strain hardening equation: $\sigma = K\varepsilon^{n}$

$$\log\sigma = \log K + n\log\varepsilon$$

$$n = \left(\frac{\partial \ln\sigma}{\partial \ln\varepsilon}\right)_{\dot{\varepsilon}}$$

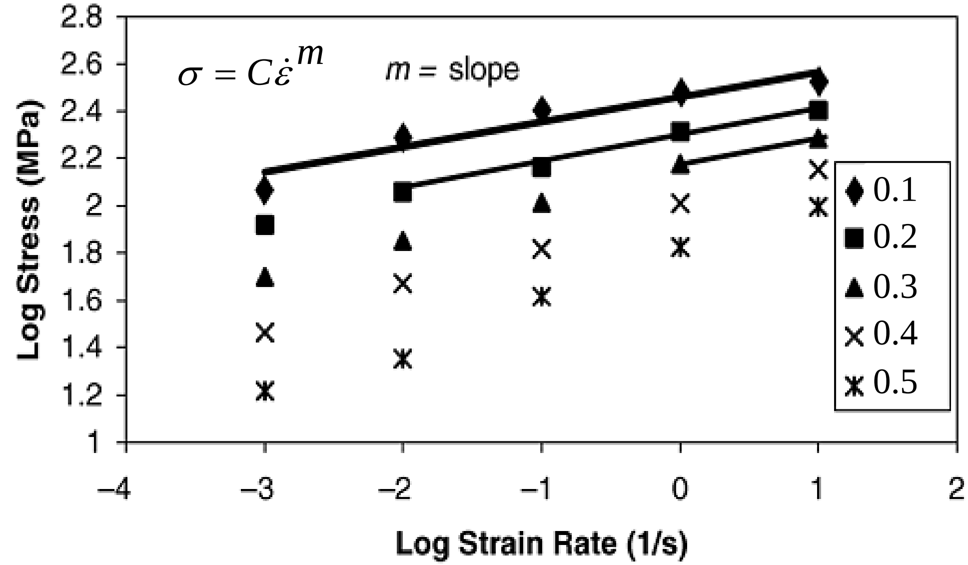
Determine Strain Rate Sensitivity “m” by Tensile Testing

Generate true stress-strain curve with different strain rates



Generate one chart for each grain size /anneal

Generate true stress-strain curve with different strain rates (ε = 0.1 or 0.15 or 0.2, TBD)

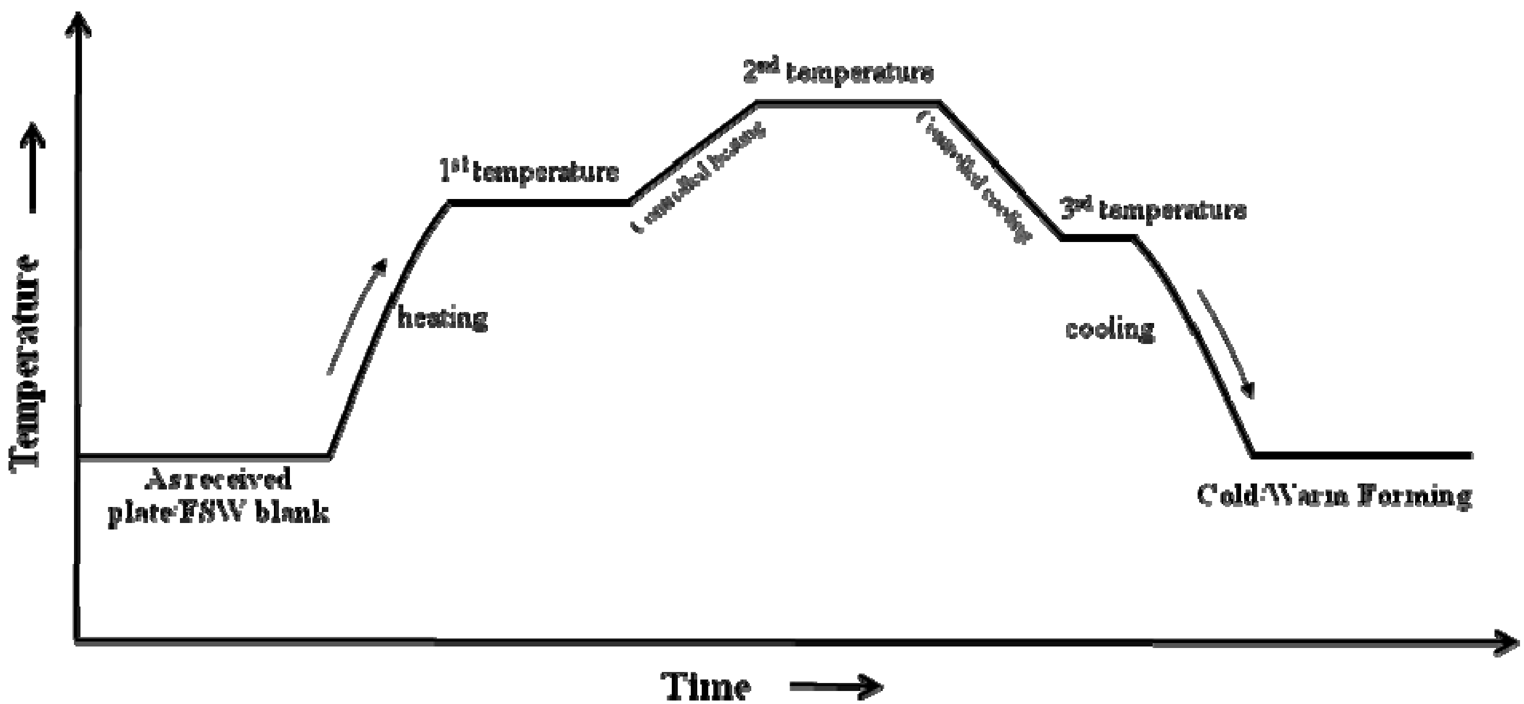


Plot log stress-strain rate for each grain size/anneal

Strain rate sensitivity equation: $m = \left(\frac{\partial \ln \sigma}{\partial \ln \dot{\varepsilon}}\right)_{\varepsilon}$

The Formability Enhancing Novel Heat Treatment Developed at MSFC

The multi-step ramp rate controlled annealing process



Capable of improving the formability for 2195 Al-Li alloy by more than 50%

Formability Study Test Matrix

Material – Weld 1 (intermediate grain size)								
				Strain Rate				
Post Weld Anneal	Temperature	# of Specimens	Orientation	0.05	1	10	100	Total # of Specimens
PW anneal 1	200 C (396 F)	1 for each strain rate	LT	x	x	x	x	4
PW anneal 2	200 C (396 F)	1 for each strain rate	LT	x	x	x	x	4

Material – Weld 3 (large grain size)								
				Strain Rate				
Post Weld Anneal	Temperature	# of Specimens	Orientation	0.05	1	10	100	Total # of Specimens
PW anneal 3	200 C (396 F)	1 for each strain rate	LT	x	x	x	x	4
PW anneal 2	200 C (396 F)	1 for each strain rate	LT	x	x	x	x	4

1. PW Anneal 1: A multi-step ramp rate controlled anneal
2. PW Anneal 2: Another multi-step ramp rate controlled anneal
3. PW Anneal 3: Anneal parameters not known, furnished by a vendor

Two welds and three anneals were used for this formability study

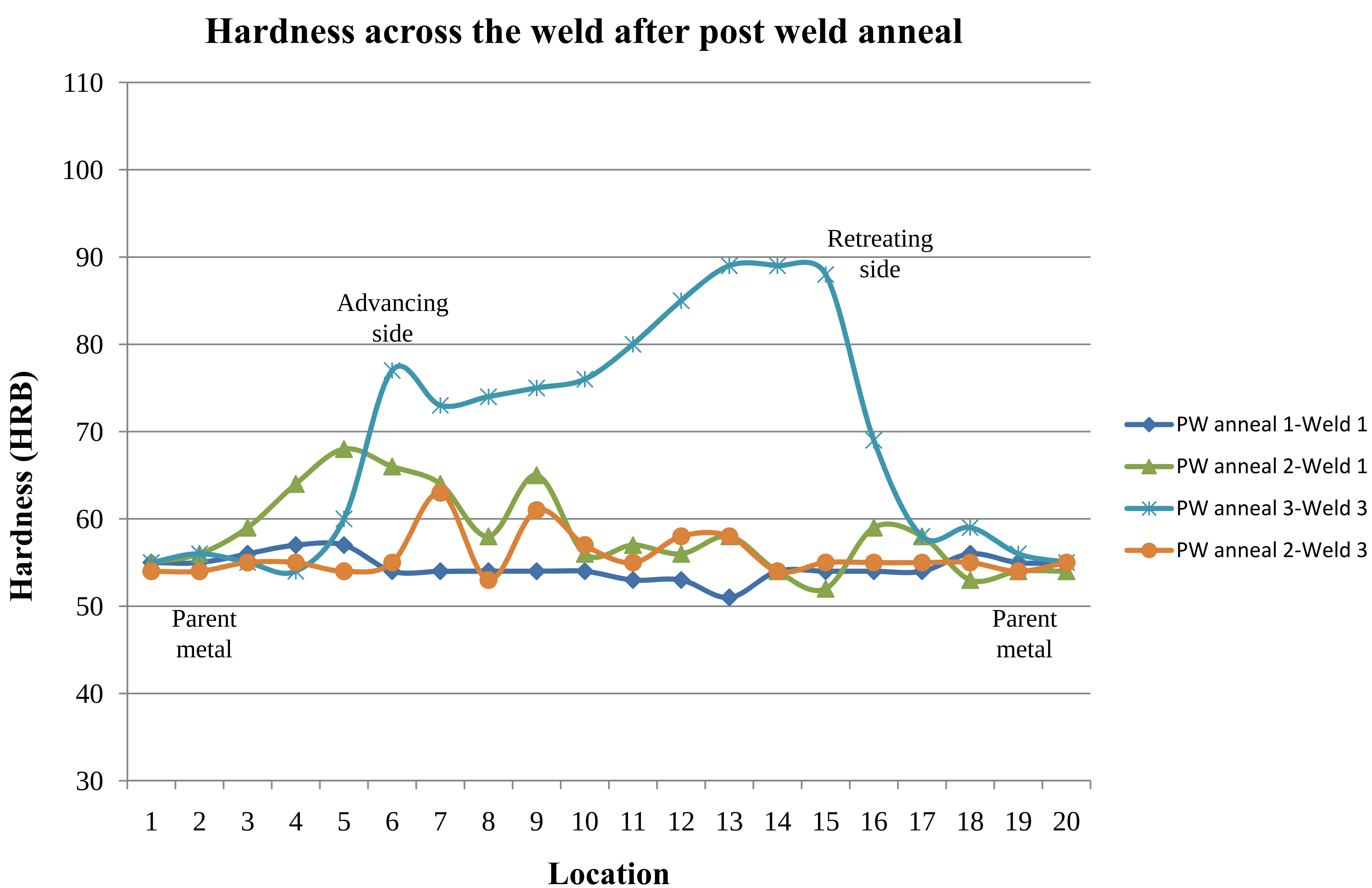
Macrostructure after Post-Weld Annealed (Weld 1 & 3)

Weld 1 – intermediate grain size

Weld 3 – large grain size

Weld 1 & 3 are very different in the shape and size of weld nugget

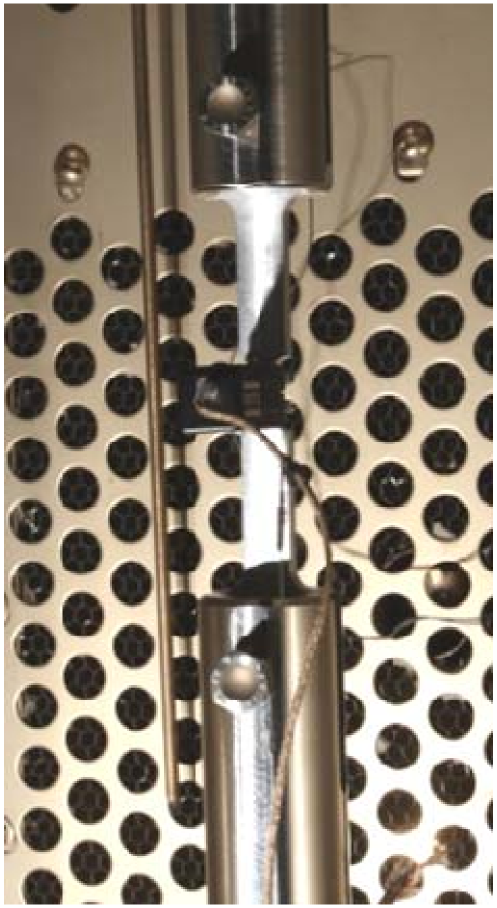
Hardness Comparison after Post Weld Anneal



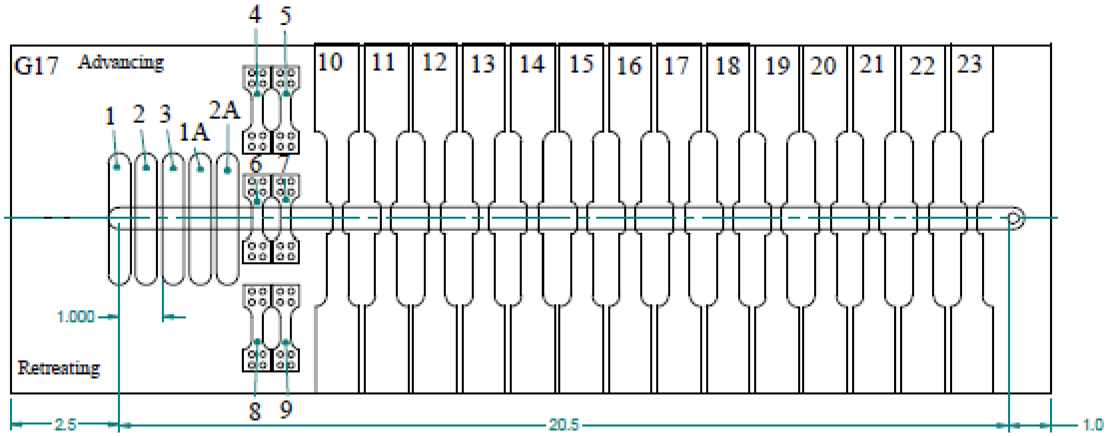
- ***Weld 3 – anneal 3 has the highest hardness in the weld nugget***
- ***Anneal 1 & 2 can equalize the weld/parent metal hardness***

Cut Plans, Sample Configuration, and Tensile Testing

Sample with an extensometer on

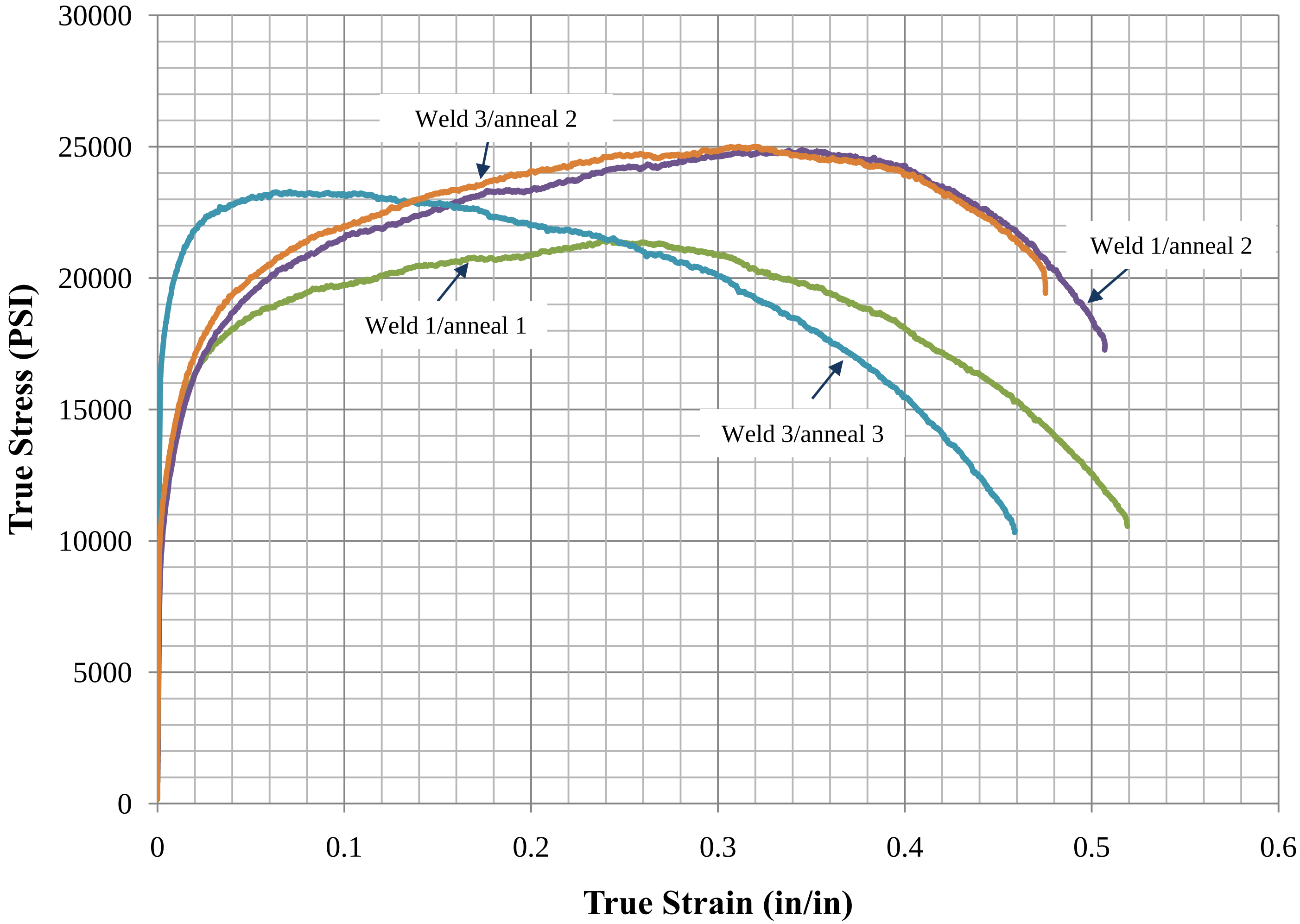


Cut plan & specimen configuration



1. 0.3” extensometer was used to record strain within the 0.5” gage section of the specimen.
2. A double reduced gage section was used to make sure the specimen necked and broke in the nugget of the weld.

True Stress-Strain Curve Comparison



- The annealing parameters have profound effects on the strain hardening behavior
- Anneal 2 has the most strain hardening effect; while anneal 3 leads to early strain softening

Effects of Post Weld Anneal on Tensile Properties

The tensile test results

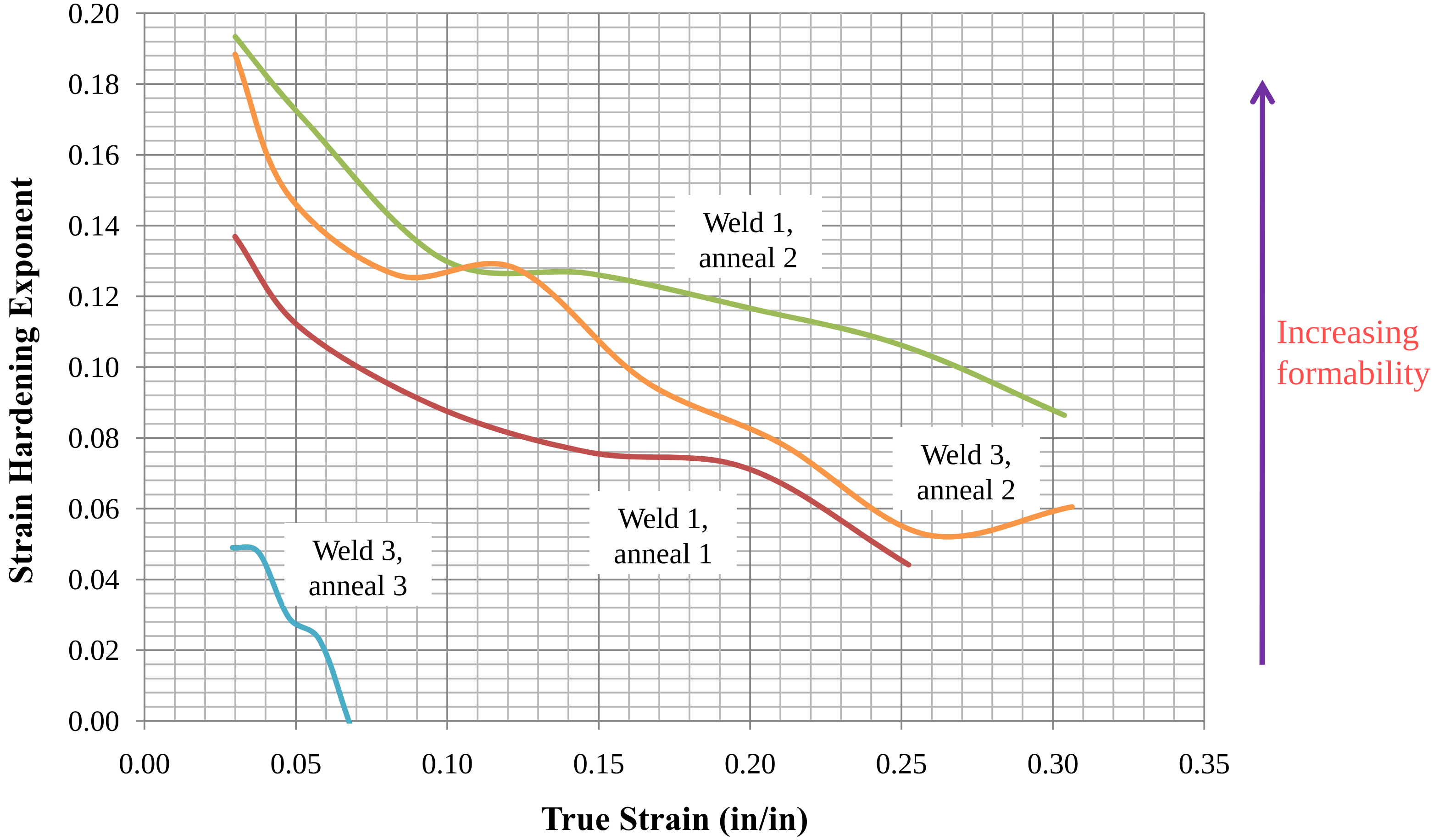
Material	Anneal	Yield Stress (KSI)	Tensile Stress (KSI)	Fracture Elongation (%)	Forming Range	Formability Ranking
Weld 1	PW anneal 1	11.5	16.6	65.9	***5.1***	*3*
Weld 1	PW anneal 2	9.3	18.0	63.3	***8.7***	*1*
Weld 3	PW anneal 3	17.7	22.0	58.2	***4.2***	*4*
Weld 3	PW anneal 2	11.5	20.0	60.8	***8.6***	*2*

Material	Anneal	**Strain Hardening, n (1 to 5% strain)**	**Strain Hardening, n (5 to 9% strain)**	Formability Ranking
Weld 1	PW anneal 1	0.16	0.1	*3*
Weld 1	PW anneal 2	0.21	0.15	*1*
Weld 3	PW anneal 3	0.08	0.01	*4*
Weld 3	PW anneal 2	0.19	0.15	*2*

1. Formability can be enhanced by using the novel heat treatment method.
2. PW anneal 2 produces the highest formability – highest forming range & "**n**"
3. PW anneal 3 produces the highest yield strength but the lowest formability

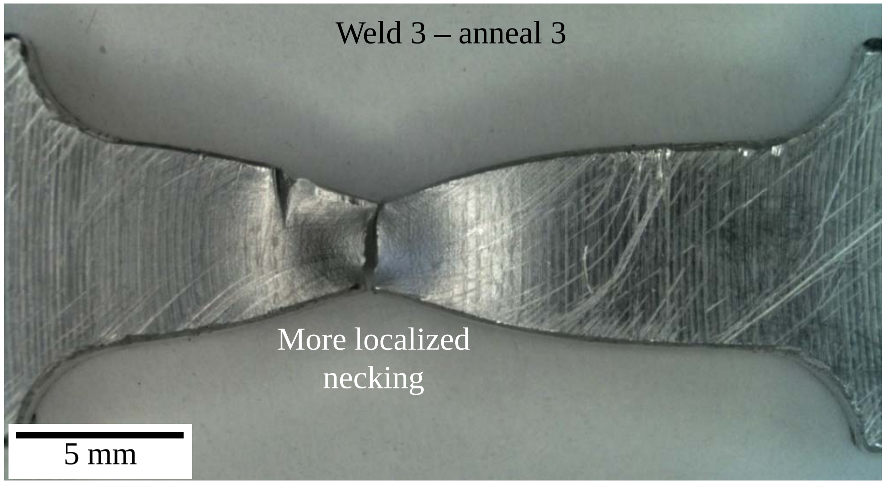
Comparison of Strain Hardening Exponentfor Weld 1 & Weld 2

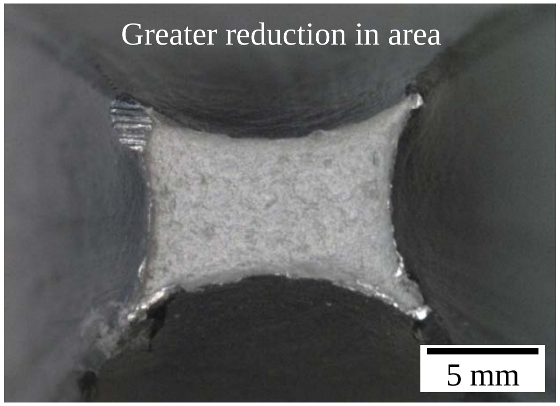
$$\sigma = K\varepsilon^{n} \qquad n = \left(\frac{\partial \ln \sigma}{\partial \ln \varepsilon}\right)_{\dot{\varepsilon}}$$

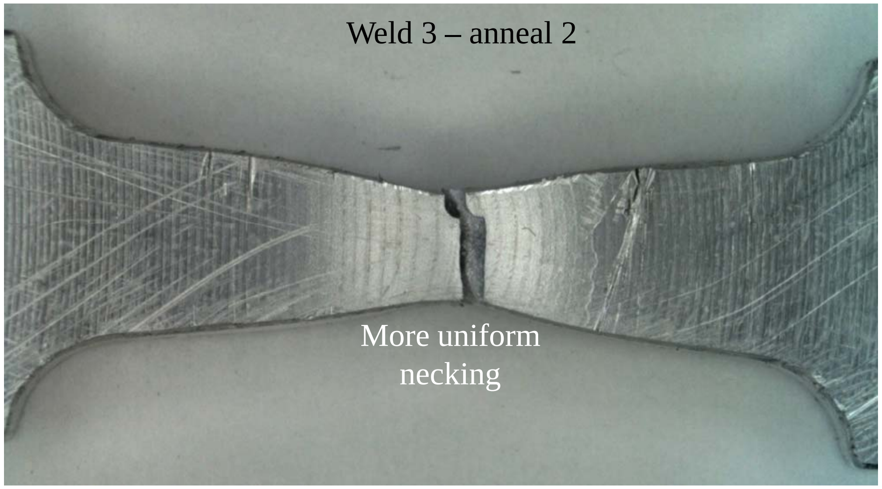


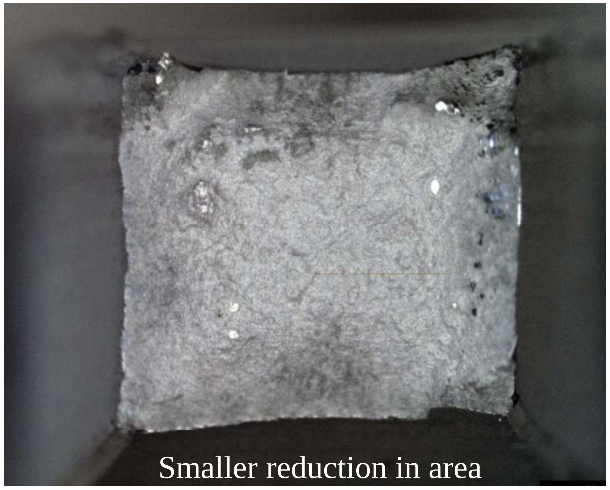
- ***Anneal 2 is very effective in increasing the strain hardening exponent***
- ***More than 50% increase in the strain hardening exponent can be achieved with anneal 2***
- ***Drastic reduction in strain hardening exponent after anneal 3 for weld 3***

Analysis of Failed Tensile Samples (Weld 3)



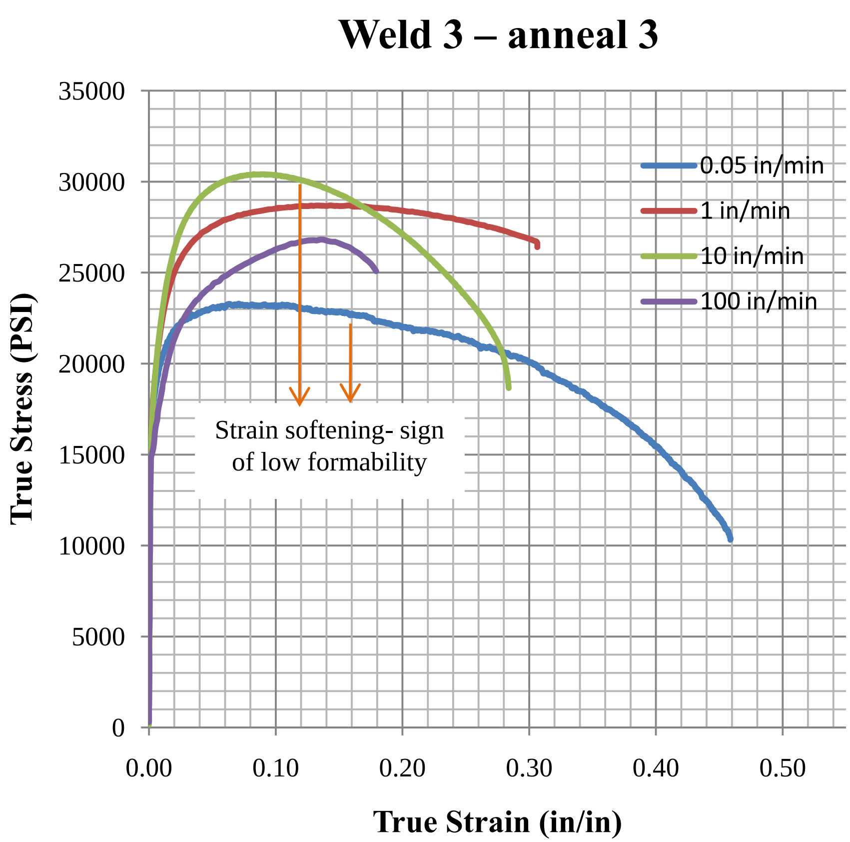


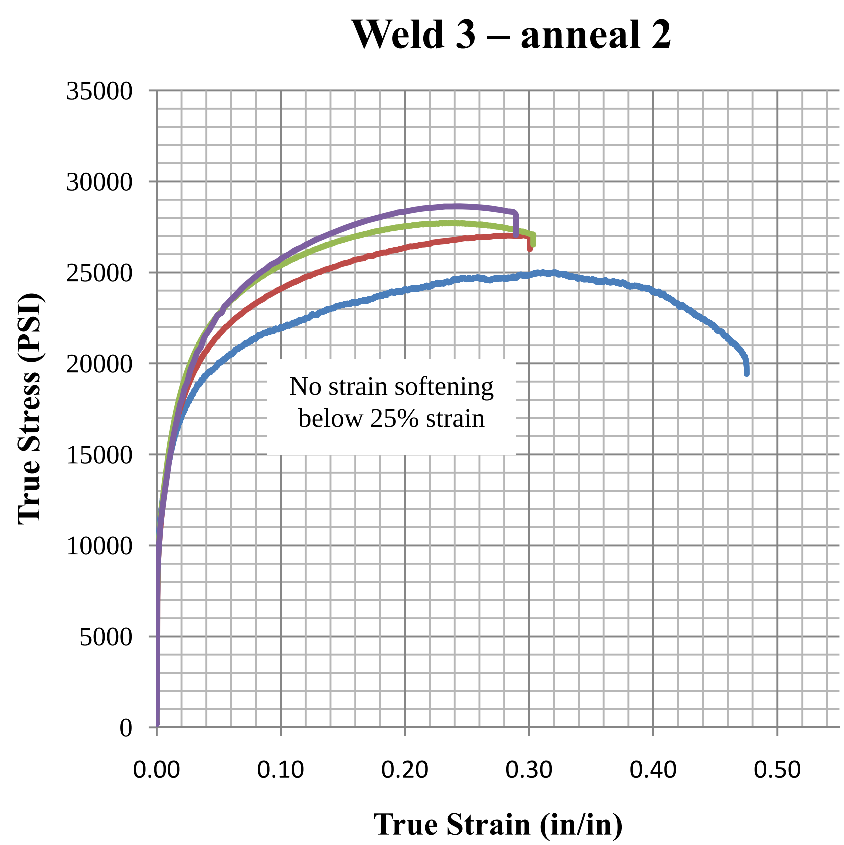




Anneal 2 can homogenize strain distribution and prevent localized necking

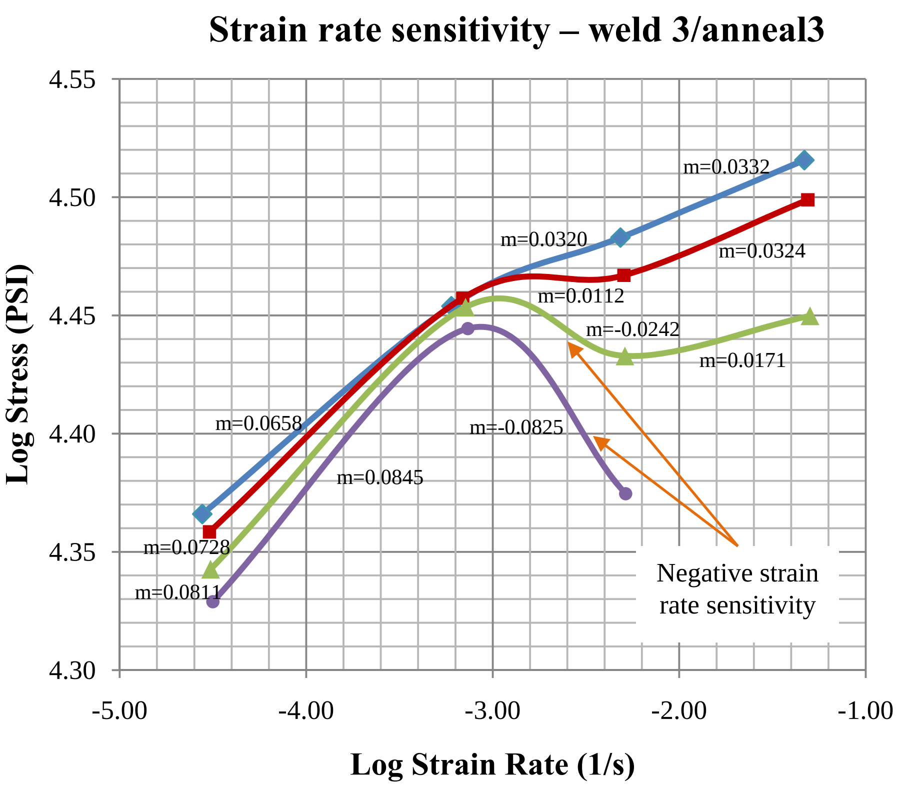
True Stress/True Strain Curves – Effects of Strain Rate & Anneal

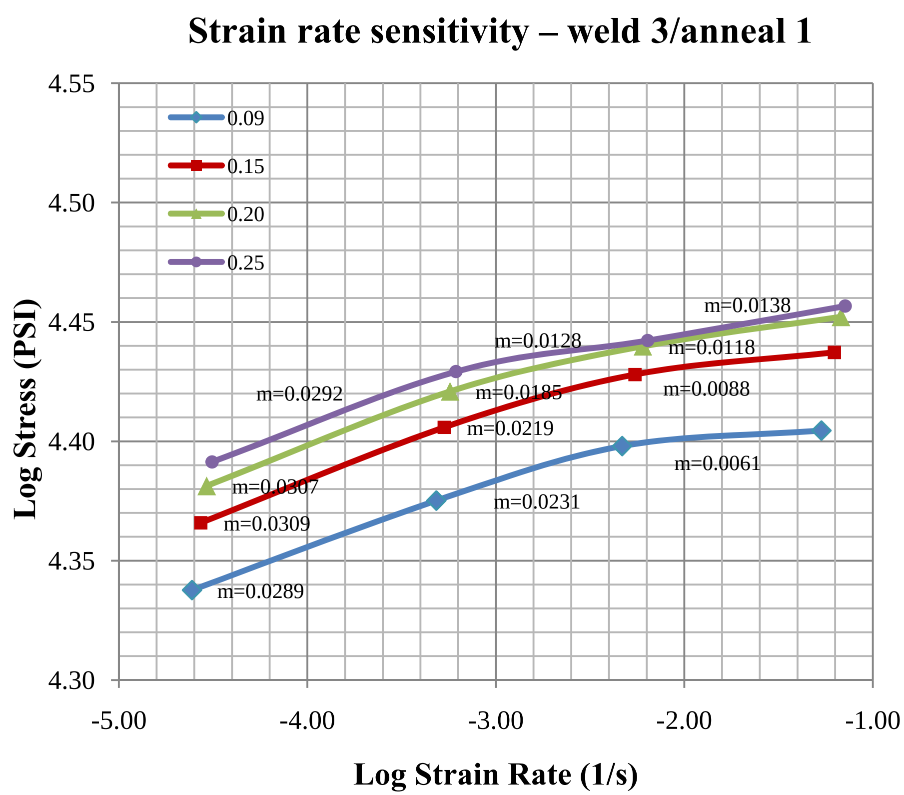




- Higher strain rate leads to higher strain hardening exponent for anneal 2
- Anneal 2 has higher strain hardening effect; while anneal 3 leads to early strain softening
- Strain softening observed in anneal 3 is a sign of poor formability

Strain Rate Sensitivity Comparison – Effects of Strain Rate & Anneal





- Anneal 3 increases the strain rate sensitivity at lower strain level
- Stain rate sensitivity turns negative at higher strain level & higher strain rate for anneal 3
- Negative strain rate sensitivity would accelerate necking & decrease formability

Summary of the Formability Study Findings

☑ **Demonstrated feasibility to increase strain hardening exponent by using the novel annealing process**

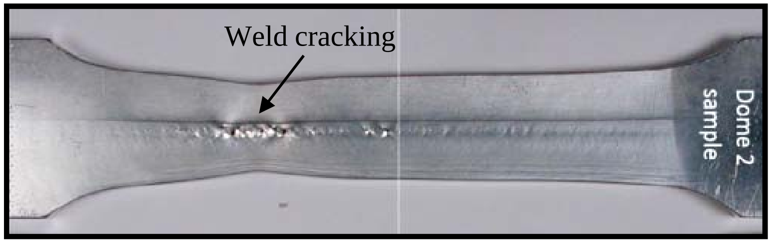
- The current post weld anneal (anneal 3) resulted in low "n"
- This the reason why the FSW is susceptible to cracking during spin forming

☑ **The formability enhancing novel heat treatment is promising**

- The "n" can be increased by more than 50%
- Forming range and ductility also increase significantly
- The "m" can be increased in the higher strain rate and higher strain regions
  - ✓ Capable of promoting more homogeneous forming strain distribution

☑ **Anneal 2 will be recommended for spin forming the cryogenic domes**

- Can lead to significant increase in both "n" and "m" – higher formability



Low weld ductility problem
can be solved by anneal 2

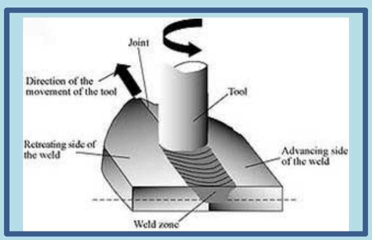
Additional Development Activities at MSFC

- **Develop welding parameters that can produce favorable weld microstructure for spin forming**
  - To enhance formability & mitigate AGG in the weld

- **Continue tensile testing to determine the strain rate sensitivity**
  - Another indicator of formability, higher strain rate sensitivity can enhance formability by defusing necking

- **Develop post-forming heat treatment (SHT+stretching+aging) that can mitigate AGG**
  - Looking into fast ramp rate heating methods and using favorable weld microstructure

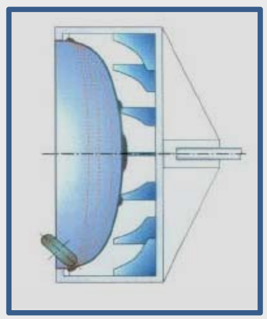
Friction stir welding



FSW development

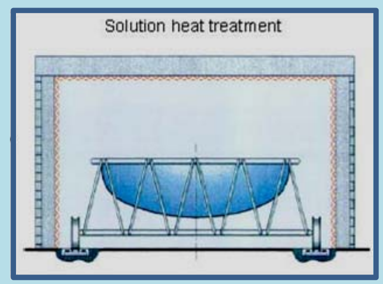
Post-weld anneal

Concave spin forming



Formability Enhancement

Solution heat treatment



AGG Mitigation